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Prerequisites and Barriers for the Development of Reconfigurable Manufacturing Systems for High Speed Ramp-up

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Abstract

Intensified global competition, fast developing technologies, and changing customer demands have resulted in a trend towards increased differences in customer requirements, increased need for customization, shorter product life cycles, shorter windows for market opportunity, and rapid new product introductions. Thus, production ramp-up is becoming a more and more important stage in the lifetime of a product, which manufacturers need to be able to handle frequently and efficiently in order to gain competitive advantage. Reconfigurable manufacturing systems (RMSs) are attractive options for handling this, as the system can be continuously reconfigured in accordance with the demanded volumes and products. However, the development of the RMS is a particularly challenging task compared to the development of a traditional manufacturing system. Therefore, the aim of the research presented in this paper is to investigate prerequisites and barriers for developing reconfigurable manufacturing. Initially, the paper presents a review of current literature on reconfigurable manufacturing with an identification of the prerequisites for its implementation. Moreover, through a long-term case study, their presence and the barriers towards their adoption and development in industry are investigated. The findings suggest multiple barriers for the successful development of reconfigurable manufacturing in industry. Conclusively, these findings are discussed and considerations for future research are proposed in order to aid the transition towards reconfigurability in industry.

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Keywords: reconfigurable manufacturing, RMS prerequisites, RMS barriers, production system development, production ramp-up.

1. Introduction

In today's global market place, customer needs are becoming increasingly dissimilar and the need for customization and new products features is intensifying [1]. Recently, a study indicated that product variety has been more than doubled in the period from 1996 to 2012, and that the duration of product lifecycles at the same time has decreased in average 30 percent [2]. Moreover, there is evidence that the time for new products to be absorbed in the market has decreased significantly [3]. In this respect, time-to-market and quick production ramp-up is becoming increasingly critical to the success of manufacturing companies, which means that the requirements imposed on the manufacturing systems have changed [4]. In the past, manufacturing systems were

developed for one ramp-up period with subsequent long and stable periods of producing only a few variants [5]. Currently, the frequency of new products is increased and time for designing, building, and ramping-up volumes has been reduced, which means that the manufacturing systems must be built for rapid change in accordance with the market [6]. For that reason, the reconfigurable manufacturing system (RMS), which can be repeatedly changed in capacity and functionality in a cost efficient way, has been widely labelled the manufacturing system of the future [7, 8].

The reconfigurable manufacturing system was initially introduced by Koren [9], as an intermediate production concept in between traditional dedicated manufacturing lines and flexible manufacturing systems. The difference between the RMS and these traditional production systems is that the RMS

can be scaled in capacity and converted between variants, due to being composed by modules that are able to be integrated cost-efficiently [10]. Moreover, one important characteristic of the RMS is that it has customized flexibility, meaning that it is designed for part and product families, thereby reducing the traditional trade-off between flexibility and efficiency [4].

Clearly reconfigurable manufacturing meets challenges in today's global manufacturing environment that traditional approaches to manufacturing are not able to [11]. In particular, the RMS concept offers a solution to the challenge of rapidly and efficiently ramping-up volumes and varieties, as its modular structure allows for reduced time for designing, building, and redesigning the system. Thus, systematic and continuous design and ramp-up are cornerstones of the RMS concept and will occur numerous times in its lifetime. However, developing manufacturing systems that are able to be reconfigured poses various challenges compared to dedicated manufacturing. Currently, various different design frameworks and methodologies exist, but their industrial application has not yet been proven. Therefore, the aim of this paper is to determine important prerequisites for designing and developing reconfigurable manufacturing systems and to investigate the barriers towards their adoption in industry.

The remainder of the paper is organized as follows: Section 2 briefly summarizes current RMS development approaches with the aim of identifying prerequisites related to developing reconfigurable manufacturing compared to traditional manufacturing system design. In Section 3, the methodology applied for investigating these prerequisites and the barriers towards them are described. In Section 4, the findings from the case study are presented, while Section 5 discusses the theoretical and practical implications of the findings.

2. RMS Development and its Prerequisites

Since the introduction of reconfigurable manufacturing, research in the area has broadened significantly and today covers many different research issues [12], e.g. manufacturing system selection and justification [13, 14], configuration selection [15, 16], process planning in an RMS [17], and scalability planning [18]. Despite the relevance of these research issues, it is important to emphasize that they mostly deal with optimizing already existing reconfigurable manufacturing systems. However, in current research, the actual successful implementation of reconfigurable manufacturing has not been widely reported, and there is a lack of support for companies transitioning towards reconfigurability in their operations [8]. Therefore, it is important to address how to develop and design reconfigurable manufacturing. In the following, current frameworks for RMS design and development will be briefly reviewed and the essential challenges and corresponding prerequisites compared to traditional design will be identified.

2.1. RMS Design Frameworks

Currently, a number of different design frameworks for reconfigurable manufacturing can be identified in research. In this respect, a design framework is defined as a term covering

a supportive structure that in some way guide practitioners towards the development of a manufacturing system that is scalable and convertible through reconfigurations.

Among the earliest frameworks found in literature is the one proposed by Abdi and Labib [13, 15, 19]. Their framework consists of three parts. The first addresses the issue of selecting the appropriate manufacturing system type and justifying its investment [19], whereas the second part contains a reconfiguration link, which groups products into families and selects the product family to produce in each configuration [15]. The last part contains the tactical design of the RMS, where the feasibility of the selected configuration is determined [13]. This design framework is a continuous design framework or a so-called RMS loop, where design requirements are continuously revised in the system's operating time, leading to a repetition of the aforementioned design steps.

This continuous design element can also be found in the framework proposed Deif and Elmaraghy [20]. They propose a three-layer RMS design architecture, where the first layer is a market capture layer, where the requirements for capacity and functionality are determined based on different market profiles. Hereafter, the system-level reconfiguration layer generates system alternatives or configurations based on the input from the market layer. A selection of the most feasible configuration ends this step, with a plan for how to change from the existing configuration to the new one. The last layer is the component-level reconfiguration layer, where the implementation of the physical reconfiguration is addressed. This three-layer framework shares similarities with the terminology used by Bi [8], who defines three types of design issues in an RMS. The first is the architecture design, where the system's components and interactions are determined. This architecture determines which configurations the system can produce. The second design issue is the configuration design, where the configurations for specific tasks are selected for operation. This phase is carried out within the window of available configurations specified by the architecture design. The last design step is the control design, where process variables are determined in order for the configuration to fulfill its given task satisfactorily. The configuration and control design are repeatable tasks in the life of the RMS, which will be carried out when requirements for the manufacturing tasks change.

Tracht and Hogueve [21] propose a design method for modular and reconfigurable assembly systems, which is divided into two phases; a design phase and a reconfiguration phase. When the designed modular system is operating, reconfigurations are carried out in response to variant changes, capacity changes, and product changes. Both the design and the reconfiguration phase are elaborated through a number of different procedures to guide the designers and planners of the system. These procedures are a combination of conventional system design steps and new procedures for modular systems, such as clustering operations and defining degree of modularity. Schuh et al. [22] approach the issue of designing modular and changeable manufacturing systems by applying object-oriented design. An essential part of this design approach is to identify change drivers external and internal to the manufacturing company, in order to determine the need for change in the designed manufacturing system. Hereafter, the

production system is described and analyzed by establishing change profiles that specify how the properties of the system element change with the change drivers. Finally, interdependencies between elements are determined and modules created.

The approach to designing reconfigurable manufacturing by Rösiö [23] differs slightly from the above-mentioned approaches, as it takes starting point in a stage-gate model for conventional manufacturing system design, and then incorporates support for considering reconfigurability.

2.2. Prerequisites for RMS Development

From the brief review of development frameworks presented above, a number of RMS system design elements can be identified, which differ from traditional design of manufacturing systems that are not modular or reconfigurable. The primary common elements contained in the frameworks are the initial determination of requirements of scalability and convertibility, a detailed design that incorporates the required degree of change by accommodating different configurations based on a modular architecture, and the continuous selection of configurations in the operating time closely integrated with product development. As these elements differ from conventional design and increases complexity of the design process, they should be regarded as challenges that may represent barriers towards the effective implementation of RMS in industry. Therefore, it is important to consider the prerequisites for performing these RMS design activities. However, despite the existence of several RMS design frameworks, there is only limited explicit concern about their prerequisites and the barriers towards adopting them. Malhotra et al. [24] derived a list of barriers related to RMS implementation from current RMS literature, such as difficult interfaces, reconfiguration of controller architecture, expensive tooling, difficulty in axes location, etc. However, these barriers are widely concerned with issues regarding RMS implementation and operation, and not explicitly with the development and design, which is of high importance as there is currently only limited evidence for actual successful implementation of reconfigurability in industry.

Rösiö [23] propose a set of questions to consider in manufacturing companies prior to engaging in RMS design. For instance, it is proposed that applying a long-term view of the system, in order for it to be economically viable for multiple product generations, is a prerequisite for RMS development. Moreover, a critical prerequisite is the ability to integrate the system design with the product portfolio, as the system should be designed for multiple product variants within a product family. Factors such as the level of staff skill and knowledge of reconfigurability, whether a structured system design process is applied, and readiness to have life-cycle perspective in production and investments are considered as additional prerequisites. Similarly, Rösiö and Jackson [25] address two important prerequisites for designing changeable manufacturing, which is having a life-cycle perspective on production systems and correlating product and production design. In Table 1, all of the RMS design and development prerequisites that can be identified in current research are listed.

Table 1. RMS Design Prerequisites

| Prerequisites |
|--|
| A life-cycle perspective on production systems [25] |
| Correlation between production system design and the product portfolio development [25] |
| Having long-term view on investments in production capacity [23] |
| Having a structured production system design process [23] |
| Having a holistic perspective on production systems [23] |
| Having staff that is skilled in system design and have knowledge of reconfigurability [23] |
| Existence of product families for customized flexibility in production [23] |

From the list of prerequisites presented in Table 1, it is evident that a prerequisite can have very different nature. In this respect, an RMS design prerequisite can be defined as a specific condition, capability, or knowledge that should be present in a manufacturing company. However, as these prerequisites differ significantly from the requirements related to developing traditional dedicated production systems, it is important to consider their presence and the barriers towards them in industry. Additionally, an even more important aspect is to consider which activities and efforts that can be carried out in a manufacturing company in order to develop these prerequisite if they are not currently present. Moreover, as the prerequisites stated here are rather intangible and elusive, it is hard to directly assess their presence, which emphasizes the need for increasing knowledge on conditions in companies that influence the ability to successfully engage in RMS design.

Therefore, the following research question has been formulated for an industrial case study: which specific barriers and conditions can be observed in a manufacturing company as having a relation to the prerequisites for developing reconfigurable manufacturing?

In the following section, the methodology applied for addressing this research question is elaborated.

3. Methodology

In order to address the research question stated above, a long-term case study has been carried out. Applying case research is based on the reasoning of Voss et al. [26] that observing actual practice will contribute with valuable understanding of which conditions in companies that could indicate whether the prerequisites for RMS design are present. In respect to this, case research is found appropriate, as the research question calls for explorative investigations, where the topic is not yet completely understood and relevant knowledge can be obtained from observing actual practice with a rather detailed understanding of the complexity involved [27].

3.1. Case Description

The case studied in this research is a large Danish enterprise that is currently in a transition towards implementing reconfigurability in the production systems, through the creation of modular production architectures and platforms. During the latest years, the company has conducted various development projects in cooperation between product

development and production engineering with the aim of defining modular product and production architectures, thereby enabling convertible and scalable production systems with increased reuse between product variants and generations.

Most recently, a development project was conducted, which elapsed for 20 weeks and involved more than 20 employees from production engineering, product development, frontloading, and specialists from different manufacturing fields. The specific scope of the project covered the assembly of five product families of both high and low variety, with a total annual production volume of approximately 4.3 million units. This project can be regarded as the company's first step towards developing reconfigurable manufacturing.

3.2. Data Collection

The case study has been conducted for a period of more than 1.5 years, through the participation in various activities and projects related to the RMS transition. In particular, intensified data collection was carried out during the latest phase of the most recent development project, which was described above. In the last 7 weeks of this project, 1-3 weekly meetings with a group of employees from development and engineering was held. In these meetings, the primary goal was to identify areas in current production where reconfigurability could be beneficial, to quantify and describe the potential, define product roadmaps and forecasts for RMS design, and determine which product families that could be included in the future design. During these meetings, one of the researchers participated in order to collect information related to the prerequisites for RMS design. The information collected primarily cover direct observations from participation in meetings, and further information from follow-up questions and unstructured interviewing. In regards to this, the generic RMS design prerequisites identified in Section 2.2 were applied as research variables, which guided the data collection.

4. Case Findings

In the case study, different interesting observations were made in a relation to the RMS design prerequisites listed in Table 1. In the following, these findings are presented.

4.1. Life-cycle perspective on production systems

Having a life-cycle perspective on production involves having a long-term view on the production system, where the system is designed to be adjusted and reused for multiple product generations throughout its entire life cycle [25].

In the case study, three specific conditions were observed as having impact on the readiness to meet this requirement. First, the mindset towards reuse of production equipment was identified as a main factor. In some instances, reusing manufacturing equipment for new generations of products was considered more complicated than building new and improved version of the system, where the development and engineering team more easily could predict and promise low cycle-times. This willingness and readiness to reuse equipment depends largely on the structure and governance of new product

introduction projects. In the case company, an approach was applied where products were designed and prototyped before the production system was specified. This made it the primary responsibility for production to relatively quickly design a system that adhered to the more or less finalized product design. In other words, separation between responsibilities of production and product design was identified as a barrier towards being able to reuse production systems throughout their entire life-cycle. In attempt to counteract this situation, the case company initiated co-development approaches between product and production design, which was received positively from both production and product development teams.

A second condition that was observed as being a barrier towards the ability to design and adjust the system for multiple product generations throughout its entire life cycle, was the division of responsibilities between development teams and operations. After the run-in of systems for the initial products, operations was given the primary responsibility for the system. However, a closer integration between development and operations would be needed if the systems were to be reused and reconfigured frequently.

A third observation made in the case study is related to defining the requirements imposed on the production system throughout its lifetime. In Section 2.2, it was emphasized that determining future requirements for scalability and convertibility requires that long-term change drivers are determined, as they indicate changes that should be responded to during the lifetime of the system [20, 22, 28]. In the case company, predicting potential changes over a period longer than a few years proved to be highly difficult, in particular in term of volume trends, the timing of new product introductions, and the type of product introduction. Doing this required commitment and actual involvement from the highest level of management, as these were the primary sources to assessing strategically dependent drivers of change. Nevertheless, the task of doing this proved to be complicated and filled with speculations and vague assumptions, which led to predictions that were considered invaluable. An approach that was suggested towards overcoming this barrier was to differentiate between types of uncertainties and the level of these so that different scenarios for production system change requirements could be developed.

4.2. Correlation between production system design and product portfolio development / Existence of product families

The integration of product portfolios and production system design is a necessity for designing and operating reconfigurable manufacturing systems. In this respect, two conditions were observed as having relation, which is the ability to define product roadmaps and the definition of product families. Considering a time line of e.g. 10-15 years with product generations, new variants, and their timing was observed as being a highly complicated task, with elements that simply could not be predicted. Therefore, reluctance towards predicting product roadmaps was observed, which created a tendency to think that everything should be as changeable as possible, because nothing was perceived as being predictable. This barrier is very similar to the last barrier described in

Section 4.1, in relation to determining long-term requirements for the system. In particular, defining the scope of products to include in the reconfigurable manufacturing system was observed as being a critical task related to correlating production and product development. The decision and settlement of what constituted a product family, and which products that were similar enough to be produced together revealed dissimilar views and knowledge within development teams. Aligning these views proved to be highly valuable in the case company, which is related to building production systems for multiple product variants and generations, but also in relation to the ability to design customized flexibility.

4.3. Long-term view on investments

Having a long-term view on investments is a necessity of being able to gradually scale production capacity and in order to be able to reconfigure the production system [23]. In the case company, the readiness towards this was complicated by two conditions. First, when new products were to be introduced, the investment plans were based on business cases with often overestimated sales. As a result, capacity of production systems was also overstated. Secondly, as investment plans were approved based on expected mature sales numbers, full capacity was built from the beginning. Therefore, as all investments were made from the beginning regardless of the expected changes in needed capacity over the systems lifetime, it could be argued that having long-term view on investment involves significant changes to current practice, as this is suited for conventional system design.

4.4. Structured system design process

As designing reconfigurable manufacturing involves higher complexity than designing traditional dedicated manufacturing systems, it is a necessity to have a structured design process that specify what, how, and when something should be done [23]. In the case company, a well-developed stage gate process was applied for new product introductions. Moreover, the awareness of this approach including knowledge of deliveries, time plans, and involved departments was relatively well established in the company. As argued by Rösiö [23], this is a very useful condition when starting the transition towards considering reconfigurability in design. However, in relation to this it should be considered, that designing and operating reconfigurable systems involves iterations and a continuous element of redesign, when changes in terms of demand, variants, or products are needed. Even though, a systematic stage gate model and the well-established usage of it act as an enabler of being able to design more complicated systems, it may in its traditional and conventional form also represent a barrier, as it is not able to handle iterations and a continuous design, reconfigurations, and ramp-up.

4.5. Holistic production system view

Having a holistic production view involves considering human, logical, and physical reconfigurations in the design stage [23]. This is built on systems theory, and is related to

structural, hierarchical, and functional views on the production system. In the case study, a number of different conditions were observed as being related to this. The first observation is related to the criticality of having detailed knowledge of the production system and its constituents, as this is a prerequisite for being able to design modular systems that can be reconfigured. In the case study, the industrial aim was to identify production platforms as an enabler of reconfigurability. Therefore, a necessity was that the designers involved in the project had both detailed knowledge on the long-term requirements imposed on the system, and detailed knowledge of its constituents and interdependencies. Moreover, going from dedicated production lines to reconfigurable lines involves a holistic portfolio oriented approach to managing production systems, where different product variants and families can be produced on the same production lines. In the case company, it was experienced how the creation of a holistic overview of the current production systems and corresponding product types was an important step in this. In fact, this proved to be a highly critical element, which constituted the foundation for all activities related to developing reconfigurability.

4.6. Knowledge and skills related to reconfigurability

Having knowledge and understanding of reconfigurability is an obvious vital first step towards its successful implementation. However, previous research indicate that industry in general lacks a clear understanding of what reconfigurability is and how it differs from general flexibility [29]. One specific observations from the case study is important in this regard and is related to the criticality of investigating, specifying, and quantifying the potential of RMS compared to traditional approaches. It was observed in the case company, that doing this created an initial positive attitude towards working on RMS development. Moreover, engaging in this activity proved to increase awareness of what reconfigurability is and how it differs from traditional approaches to manufacturing. Likewise, being able to disseminate an actual quantification of RMS potential, as described in Andersen et al. [30], proved to be a vital step towards increasing the general readiness to understand reconfigurability and its characteristics in the case company.

5. Discussion

The findings presented above have both practical and theoretical implications. First, it is noteworthy to consider that despite several decades of research in the development of RMS, there are still significant challenges and barriers in regards to its actual development in industry. For instance, the case study suggests that having a life-cycle perspective on production systems, which is one of the essential elements in RMS development, is not necessarily immediately present in companies and that adopting it may require substantial effort. In fact, it can be concluded from the findings of the case company, that starting a transition towards reconfigurable manufacturing requires important changes to development approaches, but also in the way operations and projects are governed and structured, e.g. in term of separating product and

production design, separating responsibility of design and operation, and the approach to establishing investment plans.

One of the main barriers identified in the case study was the difficulty and inability in identifying long-term requirements for the manufacturing system in terms of product and demand changes. This barrier is rather essential to the development of reconfigurability, as it relates to two essential prerequisites; having a life-cycle perspective and correlating product and production development. Moreover, an essential prerequisite for RMS development is that employees have knowledge of reconfigurability, which the case findings suggest, is not necessarily widely available in practice. As a result, future research should consider if currently available design and control methodologies offer sufficient support in terms of specific tools and procedures for practical implementation. In addition to establishing practical knowledge of barriers toward RMS development, the case study indicates some potential efforts that have been carried out in a manufacturing company in order to get one step closer to developing RMSs. For instance, the findings suggest that establishing combined project teams of product and production, working on establishing holistic overviews of production systems and product architectures, and creating similar views of what constitutes product families are potential efforts that can lead to RMS development.

6. Conclusion

The research presented in this paper aimed at identifying and investigating prerequisites for RMS design. Through an initial literature review, a number of prerequisites was identified, e.g. having long-term view on production systems and integrating product and production development. However, as these prerequisites differ significantly from the requirements related to developing traditional dedicated production systems, it is important to consider their presence and the barriers towards them in industry. Therefore, a long-term case study was carried out in a Danish manufacturing enterprise, with the aim of identifying which conditions and barriers that could be observed as having a relation to the RMS design prerequisites. The findings of the case study indicate that there are still important challenges in regards to developing RMS in industry, which should be addressed in future research.

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